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Evapotranspiration Climatonomy II: Refinement of Parameterization, Exemplified by Application to the Mabacan River Watershed

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ABSTRACT—The model of evapotranspiration climatonomy is expanded by the incorporation of feedback to account for parameter dependencies on soil moisture. The concept is applied to climatic and hydrologic data for the 46-km² Mabacan River watershed in Laguna, Philippines, in a humid tropical climate where average runoff (about 1.2 m/yr) exceeds evapotranspiration (about 0.7 m/yr) significantly. Of primary concern was the development of methods for parameter evaluation or watershed calibration. The numerical model requires input of mass and solar energy (monthly precipitation and global radiation) to predict monthly runoff, soil moisture storage, and evapotranspiration. For the investigated 12-yr period, averages of monthly runoff and the root-mean-square value of departures from the annual mean are 100 ± 22.3 mm from observations and 100 ± 20.5 mm from model simulation, with a linear correlation coefficient of 0.89. Computed monthly evapotranspiration was comparable to empirical data obtained at the International Rice Research Institute (about 10 km north of the watershed and about 65 km southeast of Manila). Weaknesses of the parameterization are discussed with the aid of model-simulated runoff for each month from January 1965 to December 1968, a sequence of a "dry", a "wet", and a "normal" year.

1. INTRODUCTORY REMARKS

Evapotranspiration climatonomy is a numerical approach to the determination of moisture storage, runoff, and evapotranspiration resulting from gravitation and the sun's work on precipitation intercepted by a natural watershed. The concept, originally developed by H. Lettau (1969) using eastern North America for illustration, has been applied to Jordan (Tahboub 1970) and to regions surrounding Bangkok, Thailand (Supornrutana 1971), and New Delhi, India (K. Lettau 1971). Besides a continental setting, these studies involved fairly large geographical areas. The 46-km² Mabacan River Watershed at Laguna, Philippines, provided a suitable location for further testing of the concept when applied to a relatively small area on a tropical island in a humid climate where runoff exceeds evapotranspiration significantly. For the integration of the basic differential equation, the coefficients were previously taken as constants throughout the year for a given watershed, especially the soil moisture "residence time" or its reciprocal, the "flushing rate". In a later application of the same algorithm to the prediction of overall pollutant concentration in the "air shed" over cities, H. Lettau (1970) integrated the corresponding equation of "air pollution climatonomy" for variable flushing frequency.

Essentially, this pilot study is concerned with the method to refine and evaluate the parameterization and feedback procedures required by the numerical model to produce estimates of monthly runoff, soil moisture storage, and evapotranspiration.

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2. BASIC MODEL OF EVAPOTRANSPIRATION CLIMATONOMY

a. The Components of the System

A descriptive scheme of the system of evapotranspiration climatonomy is given in figure 1, by analogy to the corresponding systems of "surface temperature climatonomy" and "short-wave radiation climatonomy" (Lettau 1969, Lettau and Lettau 1972). The components can be listed as follows:

Input. Mass input (of H_2O) is described by the time series of precipitation, P, per finite increment of time, Δt. Normally, P will be expressed in mm/mo. Concurrently, there is input of energy as described by the time series of solar or short-wave radiation absorbed by the unit area of the land surface considered [i.e., $F=(1-a^*)G$, where G is the global radiation and a^* is the representative surface albedo of the watershed]. Normally, F, like G, will be expressed as a monthly average of calories per square centimeter per 24 hr ($\mathrm{cal{\cdot}cm^{-2}{\cdot}24\ hr^{-1}}$), which is the same as Langleys per day (Ly/day). These units are readily converted into equivalent mm/mo with the aid of the latent heat of evaporation, L.

Output. The output, or the response function (in response to the forcing functions P and F), is the time series of exchangeable soil moisture, m, which is the volume of H_2O (normally expressed as height of the equivalent water column in mm H_2O) in the representative soil column of the land area (including ponds and reservoirs) for which the P- and F-series are representative.

Process. The process includes runoff, N, concurrently with evapotranspiration, E. While percolation, which

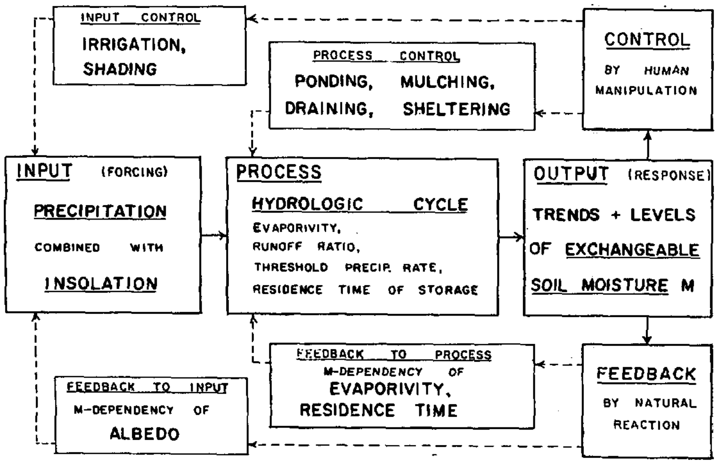

FIGURE 1.—Scheme of evapotranspiration climatonomy. The center section illustrates interconnections between forcing input (of mass and energy), process (and its parameterization), and output (or response). Control by human activity, as well as feedback by natural reactions, can affect either process or input, as illustrated with the aid of selected examples.

feeds N, is maintained by gravitational potential energy, E involves the phase change from solid or liquid to vapor requiring internal energy supply from an independent source, which, in general, is insolation (the sun's work). With the aid of mass input and output (P and m), the process definition completes the hydrologic balance,

$$N+E=P-\frac{\Delta m}{\Delta t} \tag{1}$$

where all terms are normally expressed in mm/mo.

Feedback (*naturally occurring*). The response (in the form of varying volumes of m) can cause feedback to either input, or process, or both. Examples of feedback to input are soil moisture dependencies of (1) convective instability in the atmosphere (affecting rain shower activity and, thus, mass input) and (2) surface albedo (affecting radiation absorption and, thus, energy input). There are various ways by which m variations can feed back to the processes of runoff and evapotranspiration as shall be discussed in subsection 2e.

Control (*by artificial means*). Varying volumes of exchangeable soil moisture will stimulate efforts of control, which again may be aimed at either inputs or processes, or both. Examples include irrigation, drainage, changing cropping pattern (by using alternative cultural practices and calendar of activities for such practices, multiple cropping, etc.), mulching, wind sheltering, and shading. Evidently, control operations should only be initiated if all possible feedbacks are completely understood and assessed.

b. Model Assumptions

Let the subscript i denote the i^{th} period, ending at time $t_0+i\Delta t$. If Δt equals 1 mo and the study involves a number of full years, i will range from 1 to 12, or multiples of 12. For any of the i periods, we have mass input, P_i, a soil moisture response, m_i, and process rates, E_i and N_i. It is an undeniable fact that E_i and N_i will involve not only water that is precipitated (or replenished) concurrently by P_i, but also water that had been precipitated (and subsequently stored away) by P_{i-1}, P_{i-2}, . . . during preceding periods. With this in mind, we distinguish between "immediate" process rates denoted by E'_i and N'_i, and "delayed" rates E''_i and N''_i, so that for any i value at time $t_0+i\Delta t$,

$$E_i=E'_i+E''_i$$

and

$$N_i=N'_i+N''_i. \tag{2}$$

The physical rationale for the separation is to single out the part $E'+N'$ of the time variations in $E+N$ that is directly coupled with concurrent precipitation or total mass input. With the aid of $E'+N'$, we define the "reduced" precipitation rate P'_i for any i value,

$$P'_i=P_i-N'_i-E'_i, \tag{3}$$

so that effective soil moisture changes for time steps of Δt are exactly determined by reduced input P'_i and delayed processes $N''_i+E''_i$. For convenience, the subscript i may be omitted in the following. Writing the storage term as dm/dt in place of $\Delta m/\Delta t$, we can reformulate the hydrologic balance eq (1) with the aid of eq (3) as

$$\frac{dm}{dt}=P'-(N''+E''). \tag{4}$$

c. Parameterization of the Process

Firstly, we consider the immediate processes N' and E'. During the i^{th} period, immediate runoff, N'_i, denotes that fraction of the mass input, P_i, which leaves the watershed between times t_i and t_{i+1} and, therefore, cannot contribute to the soil moisture storage term $(m_{i+1}-m_i)/\Delta t$. To parameterize N', we define a threshold value, P^*, of precipitation. As a physical characteristic of the watershed under consideration, P^* will depend on terrain slope and other drainage conditions. Because only a fraction of the excess P_i-P^* will actually be involved in N'_i, an additional parameter n^* (always positive and smaller than unity) must be defined as a physical characteristic of the watershed, whereupon, for any value of i,

$$N'=n^*(P-P^*). \tag{5}$$

N' will be used only if eq (5) produces positive values.

Immediate evapotranspiration, E'_i, during the i^{th} period denotes that fraction of effective mass input, $P_i-N'_i$, which does not contribute to $(dm/dt)_i$ because it is directly withdrawn at the surface of the watershed between time t_i and t_{i+1} by a fraction of the simultaneous input of absorbed solar energy, F_i. For any i value, we require that E' is simultaneously proportional to both the solar forcing, F, and the precipitation that is not immediately running off, $P-N'$. The relevant physical characteristic of the watershed is the "immediate evaporivity," e^*, an always positive nondimensional parameter that normally will be smaller than unity. For any given period from t_i to t_{i+1}, it measures the capacity of the land surface to utilize locally absorbed solar energy for the evapotranspiration of water precipitated during the same period. Let the annual (or multiannual) mean of F be denoted by $\overline{F}$. The defining equation for any value of i is

$$E'=\frac{e^*(P-N')F}{\overline{F}}. \tag{6}$$

In summary, for any given watershed, there are three physical parameters of the immediate process: the threshold value of precipitation, P^* (normally expressed in mm/mo), the immediate runoff ratio, n^*, and the immediate evaporivity, e^*, the last two being nondimensional.

Secondly, we consider the delayed processes N'' and E''. The important physical parameter is the characteristic time scale, t^*, of delayed soil moisture withdrawal, expressed in the same units as Δt (normally by months). Since t^* measures the "residence time" of water involved in the composite delayed process (i.e., $N''+E''$), t^* by definition must be larger than one unit of Δt. We assume also that the delayed processes vary in direct proportion to the exchangeable soil moisture, m. The defining equation is, for any value of i,

$$E''+N''=\frac{m}{t^*}$$

or

$$t^*=\frac{m}{E''+N''}. \tag{7}$$

It would be physically unrealistic to expect that the proportionality to soil moisture is the same for E'' as for N''. To separate the individual processes from the sum, we must independently define one of the two delayed processes; evapotranspiration is a natural choice. While E' represents the sun's work on water that is concurrently precipitated, E'' represents the sun's work on stored soil moisture. For any i value, we require that E'' is proportional to both the solar forcing, F, and the amount of exchangeable soil moisture, m, in excess of a threshold value m^*. The relevant physical characteristic of a watershed is the "delayed evaporivity," e^{**}, an always positive nondimensional parameter smaller than unity. For any i value, the defining equation is

$$E''=\frac{e^{**}F(m-m^*)}{m^*}. \tag{8}$$

E'' will normally be positive but may be reduced to zero if m drops below the m^* value. In eq (6), F may be expressed in any consistent units (e.g., Ly/day) because only the ratio $F/\overline{F}$ enters, but F in eq (8) must be transformed into the same units as E (normally mm/mo).

In summary, for any watershed, there are three physical parameters of the delayed process; the soil moisture residence time, t^* (which is larger than one Δt-unit), the threshold value of exchangeable soil moisture, m^* (mm of water column), and the delayed evaporivity, e^{**} (nondimensional).

According to eq (3), (5), and (6), the reduced precipitation, P', varies in proportion to actual precipitation; specifically, $P'=0$ and also $E'=N'=0$ for a month without precipitation. Equations (7) and (8) show that delayed processes vary in proportion to actual soil moisture; specifically, E'' and N'' continue to deplete soil moisture during a rainless month or a dry season until m is exhausted.

It will be shown in subsection 2d that the integration of the hydrologic balance equation involves only the sum of the delayed processes. To separate E'' and N'' from the sum ($E''+N''$) for the purpose of watershed calibration, one may introduce an abbreviation u^* for the ratio $(E''-N'')/(E''+N'')$. With the aid of this formally defined "delay-time partitioning ratio," u^*, it follows from eq (7) that

$$E''=\frac{1+u^*}{2}(E''+N'')$$

and

$$N''=\frac{1-u^*}{2}(E''+N''). \tag{9}$$

It is readily shown with the aid of E'' in eq (7), (8), and (9) that u^* is uniquely determined by m, F, e^{**}, m^*, and t^* values; that is,

$$u^*=-1+\frac{2e^{**}t^*F(m-m^*)}{m^*m}. \tag{10}$$

Equation (10) proves that u^* is not an independent parameter. The variable u^* will be used only as an auxiliary ratio in the calibration of watersheds. However, the determination of u^* is interesting because of physical significance of the special values of zero and $\pm$ unity. If $u^*\geq 1$, it would follow that $N''<0$ ("run-in" instead of runoff). For $u^*=1$, eq (9) gives $N''=0$, which makes E'' the sole delayed process. This case applies to a drainless area in an arid or semiarid climate. If the delay-time partitioning ratio, u^*, equals zero, the two processes E'' and N'' would contribute equally to the decay of an initially given amount of m. The special case of $u^*=-1.0$ indicates that there is no delayed evapotranspiration, and runoff acts as the sole decay process. A negative u^*, however, can exceed unity, and the resulting negative E'' in eq (9) would be physically possible on a watershed where condensation or dew formation is a significant climatic factor.

d. Integration of the Hydrologic Balance Equation

The parameters of the immediate process permit us to calculate the reduced precipitation, P', which represents the effective forcing function (input) for any time increment Δt. Employment of the t^* parameter of the delayed process as defined in eq (7) enables us to transform the balance equation [eq (3)] into an ordinary differential equation for m as the dependent variable; that is,

$$\frac{dm}{dt}+\frac{m}{t^*}=P'. \tag{11}$$

Let a nondimensional time variable τ be defined by

$$d\tau=\frac{dt}{t^*}$$

or

$$\tau=\int_{t_0}^{t}(t^*)^{-1}dt. \tag{12}$$

As a convenient abbreviation we define for any value of i,

$$(t^*P')_i=H_i \tag{13}$$

where H_i denotes the hypothetical water volume (measured as the equivalent height of a soil water column in mm) of the reduced mass input if P'_i would persist over a time interval equal to t^*_i. With the aid of eq (12) and (13), we reformulate eq (11) as

$$\frac{dm}{d\tau}+m=H. \tag{14}$$

For either constant or variable t^*, eq (11) or (14) is solved by

$$m=e^{-\tau}\left(m_1+\int_0^{\tau}He^{\tau}d\tau\right)=e^{-\tau}\left(m_1+\int_{t_0}^{t}P'e^{\tau}dt\right) \tag{15}$$

where m_1 is the initial value of exchangeable soil moisture for the Δt period beginning at t_0, at which time $\tau=0$. Equation (15) demonstrates that the suitable parameterization of the process results in a rigorous mathematical expression for the output, m, as a function of the reduced input, P', qualified by the parameter of residence time, t^*. Solution by differential and integral calculus rather than algebraic accounting of inputs minus independent withdrawals can be considered as the main characteristic of climatonomy.

For practical verification, we may perform a stepwise calculation yielding m_{i+1} at time $t_0+(i+1)\Delta t$, if m_i at time $t_0+i\Delta t$ is known, while the parameter t^* and the reduced input, P', and thus H, are given for both times. In principle, this method had been applied to problems of air pollution climatonomy by Lettau (1970). A computer program for the corresponding evaluation of eq (15) was developed in the course of a graduate student seminar in 1970 at the Department of Meteorology of the University of Wisconsin, and brought to useful form by T. Blasing. More recently, P. Guetter of the Department of Meteorology has cooperated in the development of a more versatile program, which performs directly the numerical integration prescribed by eq (15). The initial value, m_1, can be either independently prescribed, or rigorously determined from all monthly mean values of the parameter t^* and inputs P and G, or P'.

In the latter case, the i values of two auxiliary variables R_i and Q_i are calculated from P_i', t_i^*, and τ_i—as given by eq (12)—using the following defining identities,

$$R=\frac{e^{-\tau}}{t^*}$$

and

$$Q=\int_{t_0}^{t}P'e^{\tau}dt. \tag{16}$$

Equation (15) is reformulated with the aid of Q in eq (16) as

$$m=e^{-\tau}(m_1+Q), \tag{17}$$

whereupon division by t^* yields, with the aid of R in eq (16), and consideration of eq (4) and (7),

$$\frac{m}{t^*}=m_1R+RQ=P'-\frac{dm}{dt}. \tag{18}$$

The summation of dm/dt over all i values from 1 to a multiple of 12 (indicated by the symbol Σ) produces zero if climate and physical conditions of the watershed are stable. Consequently, summation of eq (18) yields,

$$\Sigma P'=m_1\Sigma R+\Sigma(RQ)$$

or

$$m_1=\frac{[\Sigma P'-\Sigma(RQ)]}{\Sigma R}. \tag{19}$$

Thus, with m_1 rigorously determined, the integration of the time series of reduced input, P', as prescribed by eq (15) can be performed from t_0 to $t_0+i\Delta t$, which produces the i values of exchangeable soil moisture m_i.

e. General Remarks on Parameter Evaluation (Calibration) and Account of Feedback

Our main objective is to calculate actual evapotranspiration to establish what part of solar energy is released as latent heat in different climates. In comparison with other quantitative approaches to the evaporation problem, climatonomy takes explicitly into account the fact that every water molecule evaporating from a continental surface must have been supplied to the land by precipitation. Hence, consideration of hydrologic elements is necessary because runoff also draws on precipitation.

Runoff is insignificant in certain semiarid regions. Under such "drainless" conditions, the basic equations [i.e., eq (1), (11), (15)] express only immediate and delayed evapotranspiration as withdrawal processes, with soil moisture responding to variations in precipitation and insolation absorption. For example, we refer to the discussion by K. Lettau (1973) of differences in residence time and evaporivity for a variety of grass-communities of a steppe vegetation in a semiarid climate, with parameter evaluation based on observed annual courses of soil moisture.

If runoff is significant, the evaluation of climatonomy parameters (watershed calibration) should make use of river discharge. These measurements alone will not be sufficient in climates with a pronounced winter season.

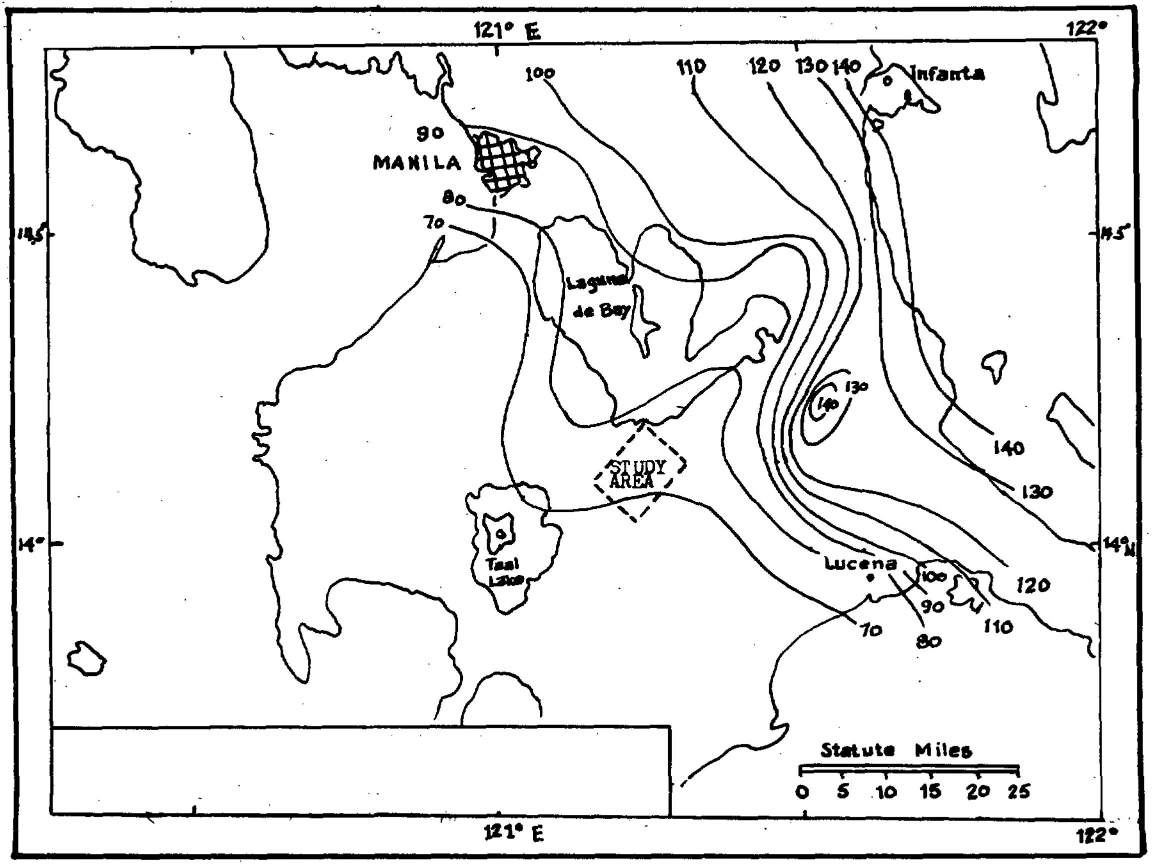

FIGURE 2.—Average annual rainfall (in./yr), after Coligado (1967), in the region of Laguna de Bay. The "study area" corresponds to the Mabacan River watershed.

In this case, parameter evaluation will be mainly concerned with the average annual course of independent meteorological elements such as occurrence of snow precipitation, and number of months with below-freezing air temperature, snow cover, and soil freeze. A significant annual variation of surface albedo, soil moisture residence time, immediate runoff ratio, and threshold values will thus result.

In climates without winter snows and freeze, the main problem will be to determine the various parameter values as functions of soil moisture. Feedback to input (to account for m dependency of albedo) or to process (to take care of possible m dependency of hydrologic cycle parameters) is allowed in the system. Operationally, this is done by using tentative parameter values in calculating a preliminary m series, which in essence is used to adjust the tentative parameters for subsequent calculation of an improved m series. The iteration is repeated until the m series generated agrees with that used to generate it. Usually, two to three iterations are sufficient. Tahboub (1970) and Lettau (1971), in their investigations of the climatonomy of regions with a pronounced dry and rainy season, employed feedback to energy input by consideration of surface albedo dependency on soil moisture via vegetation cycles in semiarid environments.

In summary, parameter values may vary from period to period Δt and from one watershed to another. They should be considered as representative area characteristics depending on topography, soil type, natural vegetation, land use, and so forth, which will undergo seasonal variations, expecially in climates with winter snow pack and soil moisture freeze. Geophysically, they belong to the same class as other more conventional climatic parameters; for example, the representative albedo, a^*, of a land area. Like a^*, the parameters for E and N processes can be determined only empirically by a "calibration" of a land area with the aid of measured or "test" values such as monthly soil moisture variations or river discharges. Practical methods and procedures for this calibration will be discussed in detail for specified land areas.

3. THE MABACAN RIVER WATERSHED

a. Geographic-Hydrologic Data

The 46-km² study area (roughly centered at 14°05′N, 121°15′E about 65 km southeast of Manila) has an average annual rainfall of about 1.9 m (figs. 2, 3). According to the data summarized in table 1, the Y-shaped Mabacan River discharges annually the equivalent of 1.2 m. This corresponds to a 12-yr mean runoff ratio ($\Sigma N/\Sigma P$) of 0.63, while 6-yr means are 0.65 for dry years and 0.61 for wet years. In the northwestern corner of the watershed, Mt. Makiling peaks at 1,090 m. The northwestern boundary rises 700 m above sea level while its downstream boundary on the northeast has an elevation of about 20 m. Coconut trees predominantly cover the area. Unirrigated upland rice, corn, sugarcane, and vegetables are planted

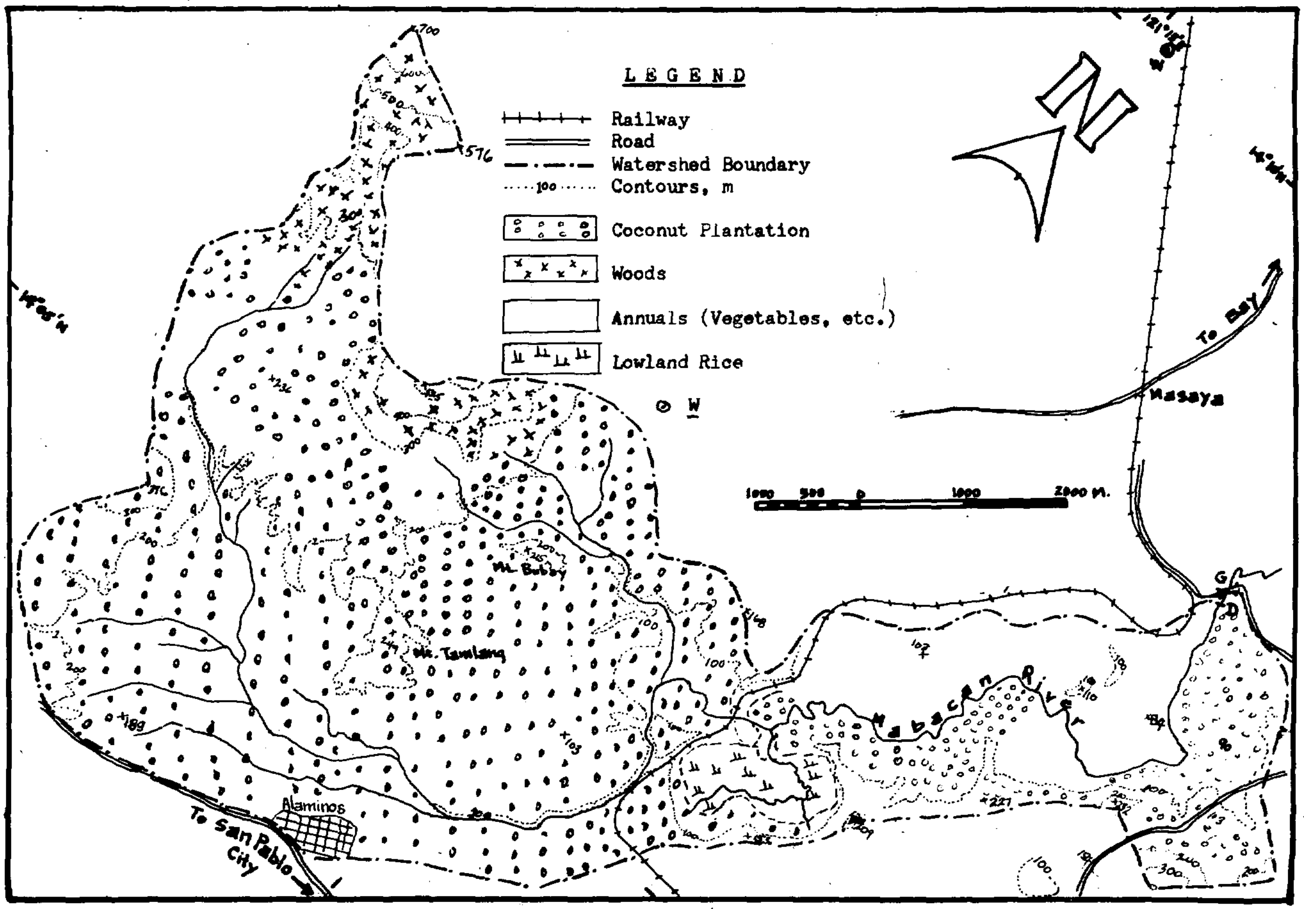

FIGURE 3.—The Mabacan River watershed, Calauan, Laguna, Philippines; G is the gaging station (14°08′ N, 121°17′ E), D is the dam site of the Mabacan River irrigation systems, W is the UPCA Weather Station (14°10′ N, 121°15′ E, 20 m above MSL).

in the relatively flat open areas or intercropped with coconut, as in the case of pineapple. A small area at the lower portion of this watershed is planted in lowland rice. The soil type is basically clay to clay loam.

The gaging station, which supplied data for runoff estimates, is about 6 km upstream from the shore of Laguna de Bay. Supplementary readings at the Mabacan River Irrigation System dam site, about half a kilometer upstream of the gaging station, were also considered, to improve the representativeness of the total river flow estimates. The observed streamflow data using staff gages may be in error by ±10 percent during the rainy season partly due to the changing cross section of the river channel at the gaging station as a result of erosion on its banks and occasional overflowing during high water stages at this time. It is indicated in the data source (Bureau of Public Works 1969) that "records are good except those above 10,000 second-liters which are fair."

b. Meteorological Data

Meteorological information was derived from the records of the University of the Philippines, College of Agriculture (UPCA) weather station located about 10 km north of the watershed (fig. 3). The normal monthly distribution of rainfall and number of meteorological rainy days for this station are illustrated in figure 4.

Data were used for the 12-yr period 1959–70. Individual years were grouped into "dry" and "wet" years according to whether the annual precipitation was below or above the 12-yr average of 1907 mm/yr. The dry years (1959, 1963, 1965, 1967–69) had on the average 1530 mm/yr; the wet years (1960–62, 1964, 1966, 1970) had an average of 2333 mm/yr. Precipitation was measured with a tipping-bucket type and a standard 8-in. nonrecording rain gage whereas an Eppley 180° type pyranometer measured global radiation.[2] Monthly means of the observational data are summarized in table 1.

TABLE 1.—*Mabacan River Watershed, Laguna, Philippines. Summary of monthly averages of observed precipitation,* P *(mm/mo), global radiation,* G *(equivalent mm/mo), and runoff,* N *(mm/mo), for all years 1959–70, and separately for 6 yr with below-average (dry years), and 6 yr with above-average (wet years) precipitation. Values for dry and wet years are 3-mo consecutive means to minimize irregular variation.*

Month:	J	F	M	A	M	J	J	A	S	O	N	D
P (all)	51	26	23	27	163	251	247	233	284	206	236	130
(dry)	61	26	18	45	98	180	223	234	186	181	152	126
(wet)	79	43	35	102	205	270	270	276	296	327	254	175
G (all)	179	202	258	286	266	226	214	196	197	204	173	162
(dry)	185	196	260	270	268	231	216	208	201	196	173	166
(wet)	190	201	257	264	263	232	223	213	199	196	180	181
N (all)	100	71	74	70	77	111	100	96	128	122	136	118
(dry)	83	80	74	73	74	84	91	92	80	88	90	97
(wet)	111	83	68	73	101	111	117	124	150	170	164	142

[2] Mention of a commercial product does not constitute an endorsement.

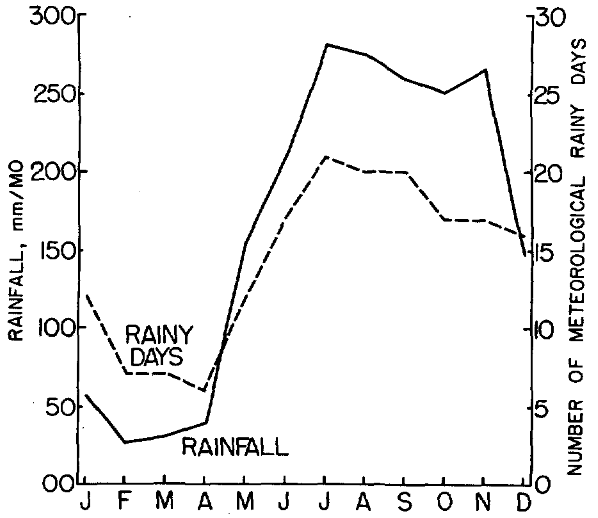

FIGURE 4.—Normal monthly distribution of rainfall and number of rainy days at the Weather Station of the University of Philippines, College of Agriculture (University of the Philippines 1969).

4. PARAMETER ANALYSIS—CALIBRATION OF THE MABACAN WATERSHED

The prerequisite for the application of the model of evapotranspiration climatonomy is knowledge of monthly values of the six process parameters (n^*, P^*, e^*, e^{**}, m^*, and t^*) and the input parameter of surface albedo (a^*). Since no previous evaluation of this nature exists, it appears justified to discuss calibration procedures in detail, with reference to the general statements given in subsection 2e. For a climate without snow and frozen ground but with pronounced contrasts between a dry and a wet season, most of the parameters will be local constants. Others (especially a^* and t^*) require consideration of soil moisture dependency. This feedback problem is solved by iterative procedures. To increase the variability of observed P and N, we will base the calibration of the Mabacan watershed on data for wet and dry years separately in the form of 3-mo running means summarized in table 1. To test the model, we will compare calculated runoff for individual months (for the 12-yr average as well as for individual years) with observations. (See sec. 6.)

Albedo measurements are not available for the Mabacan watershed. Values for tropical vegetation and field crops reported in the literature (Sellers 1965, Geiger 1966, Munn 1966, Robinson 1966) were adjusted to actual soil moisture variations between dry and wet seasons. Tentatively, it is assumed that a^* has a constant or "saturation" value of 0.14 only if exchangeable soil moisture, m, exceeds 600 mm; for drier soil, a^* increases at the rate of 0.10 per 300-mm decrease in m. This implies that for complete desiccation a^* would reach 0.34, a value which is characteristic of deserts. Obviously, $m=0$ is an extremely unlikely extrapolation for the climate of the Philippines. As will be seen later, minimum values at the end of a relatively pronounced dry season (of a dry year) will not be less than about 150 mm, so that a^* varies from 0.14 to 0.29.

TABLE 2.—*Summaries of precipitation,* P *(mm), and runoff,* N *(mm), for the month of annual* P*-maximum and the following month, and differences used to estimate the parameter* n* *from data of table 1*

	Dry years mean	Wet years mean	12-yr average
P_j	234	327	280.5
P_{j+1}	186	254	220.0
N_j	92	170	131.0
N_{j+1}	80	164	122.0
$P_{j+1}-P_j$	−48	−73	−60.5
$N_{j+1}-N_j$	−12	−6	−9.0

The immediate runoff parameters (n^* and P^*) are assumed to be constants, to be derived from the two 6-yr averages of smoothed monthly P and N in table 1 with the aid of differences for consecutive months, ΔP and ΔN. If P^*=const, the defining equation [eq (5)] yields

$$n^*=\Delta N'/\Delta P. \tag{20}$$

Let the subscript j indicate the month of seasonal P-maximum (August for the dry years, October for the wet years, according to table 1). It is postulated that the N-decrease from month j to month $j+1$ is effectively due to immediate runoff. Because $N''_{j+1}-N''_j\approx 0$ near the time of the seasonal maximum of soil moisture variation, which must follow the P-maximum, it can be concluded that the observed $N_{j+1}-N_j$ represents $N'_{j+1}-N'_j$ to a tolerable degree of approximation. Using the ratio of average differences in table 2, we get from eq (20) that $n^*=9/60.5=0.15$. When determining the threshold value P^*, it is considered that the ratio $\Delta N/\Delta P$ should show a sudden increase when, in the course of its annual trend, P begins to exceed P^*. The two series of table 1 suggest such an increase for the dry years between May (with $P=98$ mm) and June (with $P=180$ mm) and for the wet years between April (with $P=102$ mm) and May (with $P=205$ mm). The magnitude of the increase together with the above-derived n^* value narrows the choice. Tentatively, a value of $P^*=120$ mm/mo will be used.

Immediate evaporivity is also assumed to be a local constant. To determine e^*, we used the two previously established parameters n^* and P^* to calculate the time series of N' as defined by eq (5) and, subsequently, that of $(P-N')G/\overline{G}$, which equals that of $(P-N')F/\overline{F}$ if, tentatively, a^*=const. For the two 6-yr averages in table 1, it is assumed that summation of dm/dt over all 12 mo yields zero. With the aid of observed runoff, N_{obs}, the summation yields $\Sigma E=\Sigma P-\Sigma N_{obs}$; with the aid of eq (2), $\Sigma N''=\Sigma N_{obs}-\Sigma N'$. These sums are listed in table 3 together with three pairs of $\Sigma E'$ and $\Sigma E''$ formally computed for the three indicated e^* values with the aid of the defining eq (2) and (6). If e^* were chosen larger than 0.367, the E''-totals for dry years would be negative, and if e^* were chosen smaller than 0.214, the E''-totals would be larger than the E'-totals for the wet years. It is suggested that $e^*\geq 0.367$ is physically unrealistic and

TABLE 3.—*Summaries of annual totals (mm) of indicated variables derived from data in table 1 using* $n^*=0.15$ *and* $P^*=120$ *mm. Also given is the separation of* E' *and* E'' *from* $E=E'+E''$ *for three selected* e^* *values and the resulting values of* $u^*=(E''-N'')/(E''+N'')$

Quantity		Wet years total	Dry years total
P		2, 333	1, 530
N	(observed)	1, 414	1, 006
E	$(P-N_{obs})$	919	524
N'	$[\Sigma n^*(P-P^*)]$	167	66
N''	$(N_{obs}-N')$	1, 247	940
$(P-N')F/\overline{F}$		2, 148	1, 428
E'	for $e^*=0.367$	788	524
E''	for $e^*=0.367$	131	0
u^*	for $e^*=0.367$	−0. 81	−1. 00
E'	for $e^*=0.250$	537	357
E''	for $e^*=0.250$	382	167
u^*	for $e^*=0.250$	−0. 53	−0. 70
E'	for $e^*=0.214$	459. 5	306
E''	for $e^*=0.214$	459. 5	218
u^*	for $e^*=0.214$	−0. 46	−0. 62

$e^*\leq 0.214$ is unlikely. The possible range for e^* can be further narrowed only after the parameters e^{**} and m^* of the delayed processes are evaluated. Tentatively, an e^* value of 0.25 will be used for the calculation of time series of E' and E'' with the aid of eq (6), yielding the annual totals that are included in table 3, together with the resulting u^* values. The difference between u^* for wet and dry years supports the statement [made in connection with eq (10) in subsection 2c] that the delay-time partitioning ratio, u^*, is not an independent parameter.

Delay time, t^*, and the two other parameters of the delayed process (e^{**} and m^*) are determined by repeated application of the computer program described in subsection 2d. Using P and G for dry and wet years as input and a tentative albedo a^{*I} (arbitrarily selected as 0.18), we calculated the output (m^I) employing as immediate-process parameters the three constants ($n^*=0.15$, $P^*=120$ mm/mo, $e^*=0.25$) and as delayed-process parameters a tentative t^{*I} (arbitrarily selected as 3.0 mo). In the calculation of the first set of $E''^I + N''^I$ and m^I series, the constant u^{*I} values derived from annual totals [−0.53 for wet years and −0.70 for dry years (table 3)] serve to separate E''^I from the sum $E''^I + N''^I$.

The first iteration utilizes the series m^I twice. Firstly, it is used to derive a soil-moisture-dependent input parameter a^{*II}, where

$$a^{*II}=\begin{cases}0.14+\dfrac{(600-m^I)}{3{,}000}; & \text{if } m\leq 600 \text{ mm,}\\ 0.14; & \text{if } m\geq 600 \text{ mm,}\end{cases} \tag{21}$$

as independently prescribed at the beginning of this section. Secondly, it is used to obtain time series of variable delay time t^{*II} and delay-time-partitioning ratio u^{*II} by taking into account the observed runoff, N_{obs}, with the aid of the defining equations,

$$t^{*II}=\frac{m^I}{(N_{obs}-N'+E''^I)}, \tag{22}$$

and

$$u^{*II}=\frac{(N_{obs}-N'-E''^I)}{(N_{obs}-N'+E''^I)}. \tag{23}$$

The values of a^{*II}, t^{*II}, and u^{*II} serve to calculate improved time series m^{II} and E'^{II}, and, subsequently, a new series of parameters.

The decision when to stop iterations is facilitated by the construction of graphs of albedo, delay time, and of the ratio E''/F, all as functions of m. Examples are figures 5, 6, and 7 obtained for the Mabacan watershed. The consideration of E''/F is explained by the following reformulation of the defining equation [eq (8)]:

$$\frac{E''}{F}=\frac{e^{**}(m-m^*)}{m^*}=-e^{**}+\frac{me^{**}}{m^*}. \tag{24}$$

For the practical verification of the linear relationship [eq (24)], the computer program described in subsection 2d includes as printout the calculated time series of E''/F, besides m.

The following four criteria were considered for the watershed calibration: (1) parameter dependency on soil moisture should be the same for dry and wet seasons of dry or wet years, (2) the graph of E''/F versus m should produce (within tolerable error limits) a straight line so that $-e^{**}$ and m^* are given by intersects with the E''/F- and m axes, respectively, (3) the moisture dependency of delay time should be physically realistic and supported by independent observations, and (4) the calculated runoff *($N=N'+N''$) must match the observed runoff* (N_{obs}) for any month of the 6-yr averages of the test series (dry and wet years) within a prescribed and very small error tolerance (e.g., ±0.2 mm/mo) to maintain the quality of the parameterization.

Figures 5, 6, and 7 illustrate the degree of error tolerance (about ± 0.005 in a^*, ± 0.3 mo in t^*, and ± 0.03 in E''/F) with which the first criterion is satisfied for the Mabacan watershed. Figure 7 shows that the second criterion is tolerably met, yielding the constants of $e^{**}=0.0880$ and $m^*=190$ mm.

Figure 6 suggests that the main feature concerning the third criterion, the moisture dependency of delay time, is a pronounced nearly linear increase in t^*, with an increase in m, from an extrapolated 1.5 mo for $m=0$ to a maximum value of 4.8 mo for m around 480 mm; t^* decreases again, but more slowly, to 4.0 mo if m increases to 700 mm. Independent support for t^* as a function of m will be discussed in section 5. The fourth criterion is met as evidenced by the data summarized in table 4. To achieve this agreement, we ran the last two iterations with m (and subsequently a^* and t^*) remaining unchanged while u^* alone was adjusted to produce a match within ±0.2 mm/mo between observed and calculated runoff for

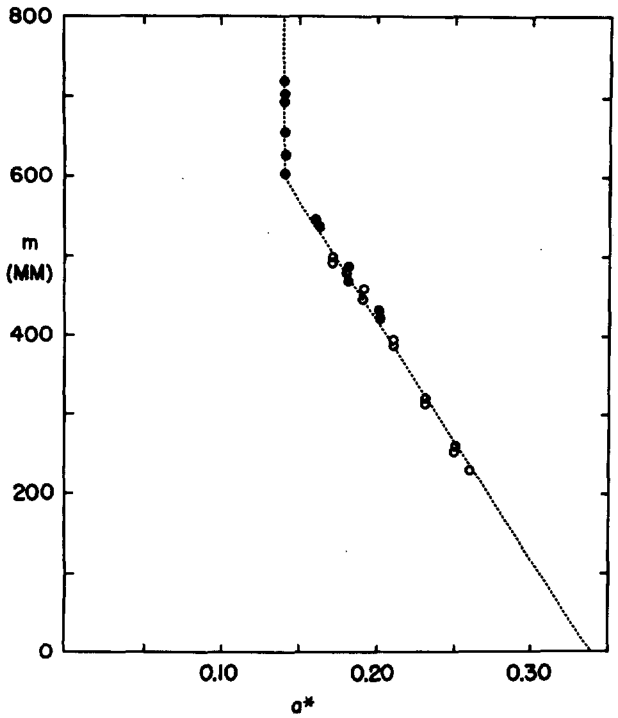

FIGURE 5.—Dependency of surface albedo, a^*, on exchangeable soil moisture, m, for the Mabacan watershed. Open circles refer to monthly means of dry years, closed circles to that of wet years. (See table 4.)

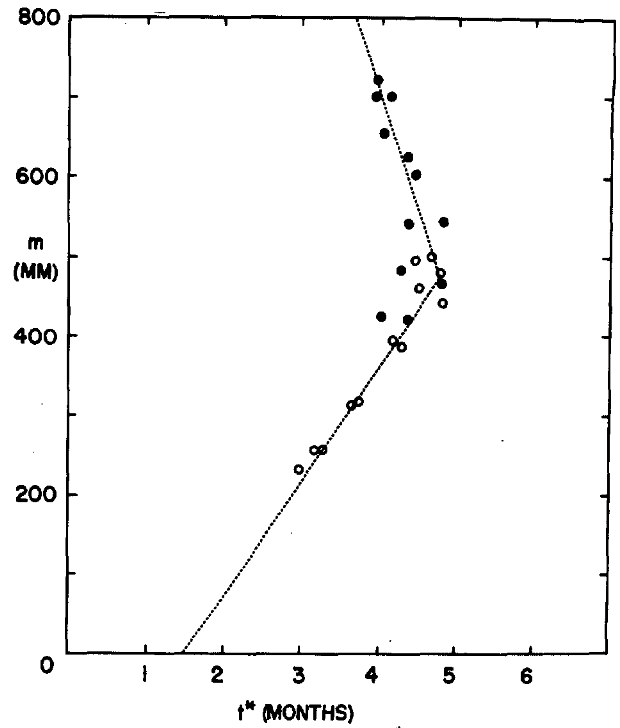

FIGURE 6.—Dependency of delay time or residence time, t^*, on exchangeable soil moisture, m, for the Mabacan watershed. Open circles refer to monthly means of dry years, closed circles to those of wet years, with reference to table 4.

any of the 24 mo of the test series. The actual model calculations are carried out with eight significant figures; the printout summarizes rounded-off figures, while for brevity certain columns in table 4 are given with further rounding-off to two or three significant figures.

In summary, the calibration of the Mabacan watershed (necessary for model simulation by evapotranspiration climatonomy) yielded minimum sets of the following five constants:

$$n^*=0.15,$$
$$P^*=120 \text{ mm/mo},$$
$$e^*=0.25,$$
$$e^{**}=0.0880,$$

and

$$m^*=190 \text{ mm}, \tag{25}$$

and the following dependencies on exchangeable soil moisture:

$$a^*=\begin{cases} 0.14, & \text{if } m \geq 600\text{mm} \\ 0.14+\dfrac{(600-m)}{3000}, & \text{if } m \leq 600\text{mm} \end{cases}$$

and

$$t^*=\begin{cases} 4.8-\dfrac{(480-m)}{145}, & \text{if } m \leq 480\text{mm} \\ 4.8-\dfrac{(m-480)}{290}, & \text{if } m \geq 480\text{mm} \end{cases} \tag{26}$$

where t^* is expressed in months. All in all, relations in eq (25) and (26) involve a total of 12 numerical factors, five in eq (25) and three for a^* and four for t^* in eq (26). On the basis of an externally given time series for input of mass and energy (P and G), these 12 factors generate the time series of soil moisture output, albedo, delay time, and immediate and delayed process rates of evapotranspiration and runoff for the Mabacan watershed as shall be demonstrated and discussed in section 6.

5. INDEPENDENT SUPPORT FOR SOIL MOISTURE-DEPENDENCY OF DELAY TIME

A priori, any of the six process parameters can depend on external conditions, like climate elements, or internal factors, like mass or energy input rates, or volume of exchangeable soil moisture. The tentative calibration discussed in section 4 suggests that five of the six process parameters can be constants for the Mabacan watershed. Only delay time or residence time, t^*, turned out to be a pronounced function of soil moisture (fig. 6). Especially important is the decrease of t^* from 4.8 to 1.5 mo as the m value of drying soil goes from about 500 mm to zero. Incidentally, in temperate climates, seasonal trends of t^* may exist that show extremely high winter values due to snow accumulation and soil freeze. Obviously, these meteorological conditions do not occur in a tropical climate. The moisture dependency of delay time summarized by relations in eq (26) must be supported by other independent observations.

It is interesting that corresponding relations are evidenced in laboratory experiments by Gardner and Hillel (1962). Potential evapotranspiration for soil samples in

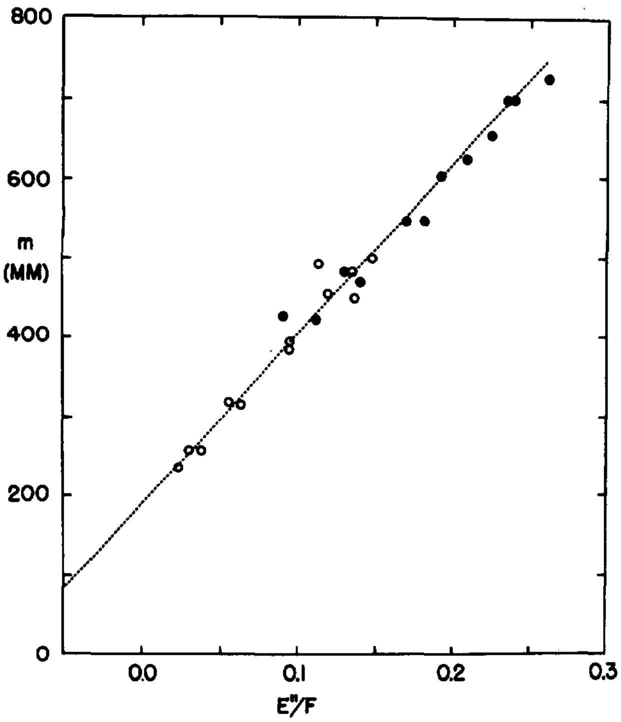

FIGURE 7.—Dependency of the ratio E''/F [where E'' is the delayed evapotranspiration in mm/mo and $F=(1\text{-}a^*)G$ is the absorbed global radiation in equivalent mm/mo] on exchangeable soil moisture, m, for the Mabacan watershed. Open circles refer to monthly means of dry years, closed circles to those of wet years, with reference to table 4.

TABLE 4.—*Verification of calibration of Mabacan watershed for evapoclimatonomy, using the numerical factors listed in eq (25) and (26). Summary of model-generated time series of exchangeable soil moisture,* m *(mm), albedo,* a**, and delay time,* t* *(mo). Also given are the immediate, delayed, and actual values of evapotranspiration* [E′, E″, E=E′ + E″ *(mm/mo)] and runoff* [N′, N″, N=N′ + N″ *(mm/mo)], with input values* (P *and* G) *for dry- and wet-year averages from table 1. Observed runoff,* N_{obs} *(mm/mo), is included for comparison.*

Variable	m	a^*	t^*	E'	E''	E	N'	N''	N	N_{obs}
Dry Years										
J	457	0.19	4.5	14	18	31.5	0	83	82.9	83
F	391	.21	4.1	6	15	20.7	0	80	80.0	80
M	317	.23	3.7	5	11	16.4	0	74	74.0	74
A	258	.25	3.3	14	6	19.6	0	73	73.1	73
M	233	.26	3.0	29	5	33.5	0	74	74.0	74
J	257	.25	3.2	44	6	50.5	9	75	83.9	84
J	317	.23	3.7	51	11	62.0	15	75	90.9	91
A	389	.21	4.3	53	16	68.8	17	75	91.8	92
S	444	.19	4.8	43	22	65.0	10	70	79.8	80
O	480	.18	4.8	41	22	62.6	9	79	88.0	88
N	500	.17	4.7	32	21	52.8	5	85	90.1	90
D	498	.17	4.5	26	16	41.2	1	96	96.9	97
Wet Years										
J	627	0.14	4.3	18	34	51.7	0	111	111.0	111
F	545	.16	4.8	10	30	40.5	0	83	83.0	83
M	468	.18	4.8	10	30	39.7	0	68	68.0	68
A	422	.20	4.4	30	24	53.5	0	73	73.0	73
M	429	.20	4.0	56	19	74.7	13	88	101.0	101
J	481	.18	4.2	65	25	89.6	22	89	111.1	111
J	545	.16	4.3	64	32	95.7	22	95	117.0	117
A	601	.14	4.4	64	35	98.9	23	101	124.0	124
S	652	.14	4.0	64	38	102.1	26	124	150.0	150
O	700	.14	3.9	69	40	109.2	31	139	170.1	170
N	722	.14	3.9	50	41	90.6	20	144	164.0	164
D	700	.14	4.1	36	37	72.6	8	134	142.0	142

cylindrical containers was monitored at a constant rate, but variable from test to test. Starting from virtual saturation ($m=M$), measurements over intervals of up to 2 mo resulted in time series of $(M-m)$ that showed clearly that the fraction m/M decreases at a significantly faster rate than the derivative $-d(m/M)/dt$. In fact, Gardner and Hillel emphasize that the derivative tends to remain fairly constant during the initial stage of drying while m/M drops from unity to about 0.5.

The climatonomic definition of residence time, t^*, is given by eq (7) and (11). For the special case of no input ($P'=0$), eq (11) yields

$$t^*=-\frac{m}{\dfrac{dm}{dt}}=-\frac{\dfrac{m}{M}}{\dfrac{d}{dt}\left(\dfrac{m}{M}\right)}. \tag{27}$$

According to eq (27), t^* must obviously decrease in proportion to m/M if the derivative should remain constant. A cursory inspection of Gardner and Hillel's data suggests that experimental delay times change from the beginning value t_0^* to about $t_0^*/2$ during the initial stage of drying. During the second stage, m/M may drop from about 0.5 to 0.1 while t^* decreases from about $t_0^*/2$ to $t_0^*/5$. In a typical laboratory experiment, using Pachappa loam, t^* is in the vicinity of 18 days, which reduces to about 9 days for $m/M=0.5$ and 4 days for m/M about 0.1.

The t^* values derived from the Mabacan watershed (fig. 7) are about 10 times larger than those from the laboratory experiments, but they exhibit in relative terms a corresponding decrease if $m<480$ mm. The difference may be due to combinations of the following four factors: (1) the thickness of the natural soil layers involved could possibly be about 10 times the 22- or 50-cm depth of the laboratory containers, (2) the constant potential evaporation in the laboratory (between 70 and 400 mm/mo) greatly exceeded the actual rates of delayed evapotranspiration in the Mabacan watershed, (3) the experiments utilized bare soil surfaces while the watershed was densely vegetated, and (4) in nature, evapotranspiration is only one of the two processes that determines the residence time in eq (7) and (11).

The delay-time-partitioning ratio, u^*, defined in eq (9), could be employed to reduce the total residence time to $2t^*/(1+u^*)$, which applies to evapotranspiration only. However, this reduction is questionable because runoff is much larger than evapotranspiration for the humid-tropical Mabacan River basin. Evaluation of data from subtropical watersheds with a significantly smaller runoff ratio would promise more conclusive results. In summary, the m dependency of t^* values shown in figure 6 appears to be qualitatively supported by laboratory studies of soil drying.

TABLE 5.—*Evapoclimatonomy, Mabacan watershed, 1959–70. Prescribed precipitation,* P, *and global radiation,* G, *constant parameters* (n*, P*, e*, e**, m*), *iterated parameters* (a* *and* t*), *and test values of observed runoff,* N_{obs}.

Month	P	G	n*	P*	e*	e**	m*	a*	t*	N_{obs}
	(mm/mo)	(mm/mo)	(–)	(mm/mo)	(–)	(–)	(mm)	(–)	(mo)	(mm/mo)
J	51	179	0. 15	120	0. 25	0. 088	190	0. 16	4. 5	100
F	26	202	. 15	120	. 25	. 088	190	. 18	4. 8	71
M	23	258	. 15	120	. 25	. 088	190	. 21	4. 2	74
A	27	286	. 15	120	. 25	. 088	190	. 23	3. 7	70
M	163	266	. 15	120	. 25	. 088	190	. 23	3. 6	77
J	251	226	. 15	120	. 25	. 088	190	. 22	3. 7	111
J	247	214	. 15	120	. 25	. 088	190	. 19	4. 5	100
A	233	196	. 15	120	. 25	. 088	190	. 17	4. 8	96
S	284	197	. 15	120	. 25	. 088	190	. 15	4. 4	128
O	206	204	. 15	120	. 25	. 088	190	. 14	4. 3	122
N	266	173	. 15	120	. 25	. 008	190	. 14	4. 3	136
D	136	162	. 15	120	. 25	. 088	190	. 14	4. 3	118

TABLE 6.—*Evapoclimatonomy, Mabacan watershed, 1959–70. Calculated absorbed insolation,* F; *immediate, delayed, and total runoff* (N′, N″, N) *and evapotranspiration* (E′,E″, E); *exchangeable soil moisture and its time change* (m *and* dm/dt); *and observed minus calculated runoff* (N_{obs}–N); m *is in mm, all other variables in mm/mo.*

Month	F	N′	N″	N	E′	E″	E	m	dm/dt	$N_{obs}-N$
J	150	0	98	98. 0	11	25	36. 5	555	−83. 5	2. 0
F	166	0	77	76. 9	6	22	28. 0	474	−78. 9	−5. 9
M	204	0	75	74. 7	7	19	26. 1	395	−77. 8	−0. 7
A	220	0	74	73. 6	8	14	22. 0	322	−68. 6	−3. 6
M	205	6	74	80. 6	46	11	57. 2	307	25. 2	−3. 6
J	176	20	84	103. 4	59	14	72. 6	362	75. 0	7. 6
J	173	19	77	96. 2	57	20	76. 5	436	74. 3	3. 8
A	163	17	81	98. 2	50	24	74. 1	503	60. 7	−2. 2
S	168	25	100	124. 7	62	30	91. 9	570	67. 4	3. 3
O	175	13	107	119. 6	49	34	82. 3	603	4. 1	2. 4
N	149	22	116	138. 3	52	30	82. 6	631	45. 1	−2. 3
D	139	2	118	119. 2	26	28	54. 0	628	−43. 2	−1. 2

6. MODEL APPLICATION—EVAPOCLIMATONOMY OF THE MABACAN BASIN

For practical use of the computer program of evapotranspiration climatonomy (described in subsection 2d), the time series of mass and energy input and of seven parameter values must be prescribed. Optionally and merely for test comparisons, other observational data such as runoff values may also be prescribed. The calibration of the Mabacan River watershed yielded the tentative parameters expressed by eq (25) and (26), which involve a total of 12 numerical coefficients. In a first application of the model, let us consider the 12-yr monthly means of mass and energy input (precipitation P and global radiation G) and test values of observed runoff (N_{obs}). These time series were given in table 1 and are summarized again in table 5, together with the five constant parameters (n^*, P^*, e^*, e^{**}, and m^*), the variable input parameter of albedo, a^*, and the variable process parameter of delay time, t^*. The latter two are the result of several iterative computer runs, beginning with the monthly means for dry and wet years derived from the data in table 4. Tentative m series were generated and used to improve a^* and t^* until agreement within error limits specified in section 4 was reached. Only results of the final iteration are listed in table 5, which correspond to the final m series in table 6. The quality of the iteration results can be objectively judged by entering individual values of a^*, t^*, and E''/F into figures 5, 6, and 7, respectively, with the aid of the individual m values of table 6.

The main results of the model calculation are the time series of absorbed solar energy $[F=(1-a^*)G]$, immediate and delayed process rates (E', E'', N', N''), and the volume of exchangeable soil moisture, m (table 6). The quality of the model prediction can be tested directly by comparing the calculated runoff, $N=N'+N''$, with N_{obs}. It follows that N_{obs} has an annual average of 100 mm/mo and a root mean square (rms) value of month-by-month departures from its annual average of ±22.3 mm/mo, while the calculated N has the same annual average and a corresponding rms value of ±20.5 mm/mo. The correlation coefficient between the 12 values of N_{obs} and N is 0.89. A graphical illustration of the two annual courses would reveal that the calculated N shows slightly smoother variations than N_{obs}.

While delayed runoff, N'', exceeds during all months the immediate rate, N', delayed evapotranspiration, E'', is larger than the immediate rate, E', only during the relatively dry months from December through April. For the other 7 mo, and on the annual average, $E'>E''$. The value of immediate evaporivity, $e^*=0.25$, chosen in section 4 is partly responsible for this result. The following brief discussion of independent estimates of local evapotranspiration rates in the general area provides no justification for a substantial modification of the tentative e^* value of 0.25.

Several field studies have been conducted near the Mabacan watershed using the conventional "potential" evapotranspiration concept, where "water is a nonlimiting factor." For irrigated lowland rice under field conditions, workers at the International Rice Research Institute (IRRI), about 1 km east of the UPCA weather station, came up with 4 mm/day as the average value of evapotranspiration for the period Aug. 14–Dec. 2, 1964 (IRRI 1964). The year 1964 had more than average precipitation. For the months of August through November of wet years, climatonomy predicts an average evapotranspiration of 100 mm/mo corresponding to 3.3 mm/day, according to table 4.

An earlier study (IRRI 1963) showed the evapotranspiration range to be 1.93–7.82 mm/day. Actual measurements from Dec. 16, 1958 to Apr. 16, 1959 and from May 16, to Sept. 16, 1959 at the weather station site, using upland rice planted on evapotranspirometer tanks well supplied with water, averaged 6.1 and 3.7 mm daily, respectively (Jesuitas et al., 1961).

TABLE 7.—*Evapoclimatonomy of the Mabacan River watershed. Model simulation (using the same notation as in tables 5 and 6) for all individual months of three consecutive years (1965 relatively dry, 1966 relatively wet, and 1967 with near-normal* P)

Year	Month	P	G	m	a^*	t^*	E'	N'	E	N	N_{obs}
1965	J	34	173	580	0.15	4.4	7	0	34	105	116
	F	10	228	480	.18	4.7	3	0	28	77	82
	M	20	262	392	.21	4.1	6	0	25	76	88
	A	80	302	336	.23	3.7	26	0	42	74	91
	M	134	248	324	.23	3.6	35	2	47	80	84
	J	91	238	313	.24	3.4	23	0	34	82	89
	J	238	202	349	.22	3.8	49	18	60	98	88
	A	107	238	375	.21	4.0	28	0	45	78	81
	S	123	222	370	.22	4.1	30	0	44	76	84
	O	84	211	358	.22	4.0	20	0	32	77	73
	N	174	176	372	.22	4.1	32	8	44	87	47
	D	122	160	396	.21	4.3	22	0	34	80	71
1966	J	36	200	364	.22	4.0	8	0	21	79	63
	F	24	245	299	.24	3.6	6	0	16	74	51
	M	22	284	236	.26	3.1	7	0	11	72	59
	A	4	331	174	.28	2.7	1	0	1	64	56
	M	442	219	278	.25	3.5	91	48	98	121	90
	J	194	258	396	.21	4.3	53	11	72	84	66
	J	168	219	429	.20	4.6	40	7	59	81	70
	A	199	238	464	.18	4.9	51	12	76	82	71
	S	202	191	506	.17	4.7	42	12	66	97	100
	O	140	181	523	.17	4.7	29	3	52	91	99
	N	410	174	606	.14	4.3	77	44	106	156	126
	D	423	150	742	.14	3.9	69	45	102	203	233
1967	J	174	149	760	.14	3.8	30	8	64	174	110
	F	12	201	652	.14	4.4	3	0	40	111	79
	M	11	241	532	.16	4.8	3	0	35	79	76
	A	17	292	439	.19	4.6	6	0	33	68	60
	M	21	285	358	.22	3.9	7	0	24	75	60
	J	233	232	363	.22	3.9	55	17	70	96	82
	J	126	220	394	.21	4.2	31	1	47	78	71
	A	297	162	463	.19	4.8	50	27	67	106	94
	S	268	213	554	.16	4.5	62	22	92	115	107
	O	178	198	582	.15	4.5	40	9	71	108	74
	N	428	152	666	.14	4.0	70	46	99	184	365
	D	37	160	656	.14	4.2	14	0	70	100	84

Covering the period 1947–66, Gomez (1969) used Thornthwaite's method of estimating evapotranspiration for the same watershed. The model of climatonomy yields estimates lower than those by Gomez with an average monthly difference of about 54 mm. There are also discrepancies in the average yearly streamflow of 140 mm. However, the Gomez data on observed streamflow excluded discharge of Mabacan River water to the irrigation system some 500 m upstream of the gaging station.

Tables 4 and 6 show that exchangeable soil moisture, m, reaches its peak level in November, amounting in dry years to 500 mm while lagging 3 mo behind the precipitation maximum and in wet years to 722 mm while lagging only 1 mo behind the precipitation maximum. The annual minimum occurs in April in wet years and in May in dry years and normal years, with values of 233 mm in dry and 422 mm in wet years. For agricultural purposes, information on exchangeable soil moisture and rates of its effective recharge and withdrawal has more direct relevance than precipitation per se since the latter includes a portion that goes to immediate processes of runoff and evapotranspiration.

In a second application, the model of evapoclimatonomy can be used to generate soil moisture, evapotranspiration, and runoff values for each individual month of several consecutive years. In principle, the number of years is unlimited. The only information needed are the time series of monthly mass and energy input rates (P and G) for the study period, since 12 numerical values, which describe all parameters, can remain the same as quoted in eq (25) and (26). For brevity, the model application will be discussed only for the period from January 1965 through December 1967. With the average precipitation for 1967 (150 mm/mo) close to the 12-yr average (159 mm/mo), 1967 represents a normal year, while 1965 is an example of a dry year and 1966 is a wet year. Table 7 contains the time series of input data (P and G), variable parameters (a^* and t^*), computer-generated immediate and total process rates (N', N'', E', E''), as well as exchangeable soil moisture, m, and also, for test comparison, observed runoff, N_{obs}. Constant parameters are the same as listed in table 5, and, therefore, are not included in table 7. Furthermore, to save space, process rates are rounded off to the nearest mm/mo.

Mass input varies greatly, the extreme minimum (4 mm in April of 1966) is immediately followed by the highest maximum (442 mm in May of 1966). Despite the tropical latitude, global radiation too varies relatively strongly, from a minimum of equivalent 149 mm/mo in January 1967 to a highest value of equivalent 331 mm/mo during the dry month of April 1966. The 3-yr time series of exchangeable soil moisture clearly reflects the overall precipitation pattern of each individual year, smoothed somewhat due to the prevailing delay time of approximately 4 mo. The highest and lowest volumes of exchangeable soil moisture during the three years are 760 and 174 mm, respectively.

It was mentioned in subsection 2d that the computer program allows for two alternatives concerning the initial value m_1. For climatic studies of monthly means in average years, it is most appropriate to use eq (19); this was done for the calculation of data listed in tables 4 and 6. It is appropriate to prescribe an initial m_1 value for sequences of individual years or to generate it by applying the model to the preceding year. The data in table 7 were calculated by prescribing an initial m_1 value. Repeated application of the computer program with a given time series of input data, but for a variety of m_1 values, serves to demonstrate that normally the effect of the m_1 choice gradually diminishes to insignificance after time intervals of about $2t^*$ to $3t^*$. Thereafter, the integration result using eq (15) becomes independent of m_1 and is completely controlled by the time series of reduced input, P', provided, of course, that $P' \neq 0$, which means exclusion of a drought period.

Table 7 shows that calculated runoff may depart con-

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siderably from N_{obs}. The extreme departures occurred in January and November of 1967, with −64 and +181 mm, respectively. The discrepancies have several causes. Firstly, the uncertainty of N_{obs} estimates increases with increasing streamflow; refer to subsection 3a. Secondly, it is unlikely that a single rain gage yields information representative of the entire watershed (Rodda 1971). As described in subsection 3a, the upper parts of the Mabacan watershed rise some 700 m above sea level whereas the UPCA weather station is only 20 m above sea level and about 10 km northeast of the center of the study area (figs. 2, 3). Rainfall observations from September 1917 to September 1919 at three elevations of Mt. Makiling show an increasing amount with elevation (McLean 1917, 1918, 1919). However, these rainfall measurements, besides being on the northeastern side of Mt. Makiling whereas the watershed is on the southeast, have been discontinued and no reliable rainfall measurements are available from the watershed itself.

Considering rainfall due to orographic uplifting and the prevailing southerly direction of the wind during the peak rainy months (June to September), one may reasonably expect multiannual average rainfall in the watershed to be greater than that measured at the UPCA weather station. If this is so, the calibration method outlined in section 4, which generates total runoff within ±0.2 mm/mo of the observed streamflow, may cause an underestimation of total evapotranspiration. Likewise, global radiation measured at a single lowland station may not be satisfactorily representative of the entire watershed. The evaluation of possible soil moisture dependency of the parameters that were tentatively assumed constant for the Mabacan basin will definitely require fully representative empirical information on watershed precipitation and discharge.

In summary, it must be concluded that uncertainties in the available test values prohibit a further refinement of the tentative calibration results developed in section 4. The parameterization of the problem, however, appears to produce a useful simulation of climatic trends for average years, but is only moderately satisfactory when applied to individual years.

7. SUGGESTIONS FOR FUTURE WORK

The monthly estimates of evapotranspiration, exchangeable soil moisture, and even runoff itself should be considered tentative until confirmed by independent theoretical and/or empirical schemes. One theoretical possibility is to integrate evapotranspiration with surface temperature climatonomy. The two systems are closely related physically since the solar energy absorbed at the ground surface is an input in both, whereas latent heat usage in the evapotranspiration of water is one of the physical processes involved in surface temperature climatonomy. This close physical relationship suggests that, for the energy requirement in calculating surface temperature, one should use the residual of the solar energy absorbed at the ground surface after accounting for the latent energy involved in evapotranspiration.

Studies of evapotranspiration climatonomy for regions with pronounced winter seasons are in progress. However, further developments for watersheds in the Tropics and subtropics are desirable. The parameterization of delayed as well as immediate processes could be made more flexible. Immediate runoff may occur even during months that have a low total but high-intensity precipitation. On several occasions (e.g., June 1960 and September 1962) heavy rainfall occurred in the Mabacan basin toward the end of the month resulting in runoff being recorded in the succeeding month. To correct this phase lag between observed runoff and precipitation, and consequently between computed and observed runoff, time increments (Δt) less than one month could be used, perhaps on the order of 1 week.

The uncertainty of streamflow data during the peak rainy months suggests further field investigations of the gaging set-up, and the identification of possible groundwater sources of the Mabacan River discharge. Even more important would be a network of at least three additional rain gage stations for a more satisfactory coverage of the study area and, possibly, at least one additional pyranometer station at a higher elevation. Measurements of surface albedo, at least in the form of occasional airplane surveys during the wet as well as the dry season, would also be helpful.

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